13B.6 STRUCTURE AND CHARACTERISTICS OF LONG LAKE AXIS-PARALLEL LAKE-EFFECT STORMS

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1. INTRODUCTION

Lake-effect snowstorms which form parallel to the long axis of a Great Lake can produce enormous snowfall rates and total storm accumulations (> 8 cm hr^{-1} and > 130 cm, respectively). Niziol et al. (1995) give a thorough description of these severe local storms. These storms have also been observed to become electrified with significant lightning production (Moore and Orville 1990). They have significant societal impacts and can shut down a community for days (e.g., Lake Storm Iron paralyzed the Oswego, NY area for 3 days in late January 2004; NWS Buffalo 2008). It is difficult to forecast the initiation, demise, changes in location, and intensity of these narrow storms (width is typically < 20 km). Indeed, Ballentine and Zaff (2007) showed that the Weather Research and Forecasting (WRF; Skamarock et al. 2005) modeling system had significant errors in forecasting band characteristics between 6 and 36 hours from model initialization. For example, the simulated band location had a persistent south bias for both model cores (NMM and ARW) by approximately 14 km.

Long lake axis-parallel (LLAP) bands have a different structure and dynamics compared to the wind-parallel rolls (WPR) mainly associated with the western Great Lakes (e.g., Kelly 1982). Kristovich and Steve (1995) show that LLAP-type bands (they call them shore-parallel bands; SPB) increase in frequency the farther east the lake is located (i.e., Erie and Ontario as the prevailing wind during the winter is more likely to cross the longest axes of these lakes). Incidentally, we do not agree with the term "shore-parallel" band as it doesn't discriminate which shore the band is parallel to (short or long axis of the lake). Indeed, 32% of lake-effect bands over Lake Ontario are of the LLAP type, while ~10% of lake-effect cloudiness over the western lakes of Superior, Michigan, and Huron were associated with these intense storms. When checking the literature the authors believe there has not been enough research attention given to these more intense storms that can affect more people when contrasted with WPR-type bands.

2. BAND TYPE CLIMATOLOGY

We examined radar reflectivity data of lake-effect events from 1996 to 2000 for the months of October through March to determine the relative frequency of long lake axis-parallel (LLAP) lake-effect storms over the eastern Great Lakes [this region experiences the greatest frequency of these storms according to Kristovich and Steve (1995)].

Figure 1 shows LLAP storms occurred two-to-three times more frequently than their wind-parallel roll counterparts. Lakes Erie and Ontario had on average more than 14 LLAP events per lake-effect season. These results show an even more preponderance for these intense storms than Kristovich and Steve (1995) showed for this region (e.g., only 32% of lake-effect cases were of the LLAP-type for Lake Ontario in their study). It should be noted that their analysis was restricted to daytime as they used visible satellite data. Using radar data expanded our study and we believe gives a more accurate assessment of these band types. Anecdotally, the lead author has witnessed LLAP snow bands are more frequent and vigorous during the early morning hours.

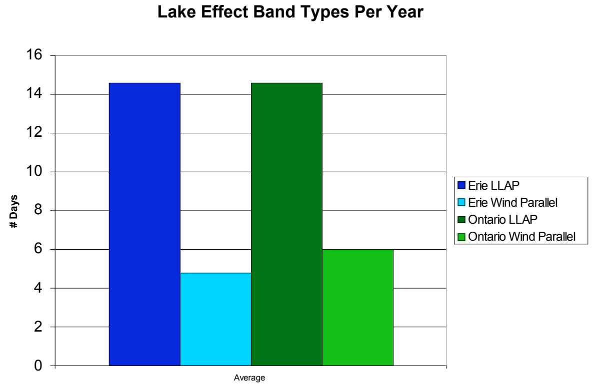

Figure 1. The mean annual number of days (from 1996-2000) when long lake axis-parallel (LLAP) lake-effect storms occurred versus wind-parallel roll bands for Lakes Erie and Ontario.

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3. LLAP BAND SIMULATED STRUCTURES

We ran an 8-km horizontal resolution, 31-level Nonhydrostatic Mesoscale Model (NMM) version of the Weather Research and Forecasting (WRF) modeling system to simulate an intense long lake axis-parallel (LLAP) lake-effect snow band which occurred in early February 2007 [Lake-effect storm “Locust;” see report at NWS Buffalo (2008b)]. This storm event deposited over 350 cm (140 inches) in Redfield, NY over a 10 day period! Figure 2 shows a radar reflectivity image of this storm.

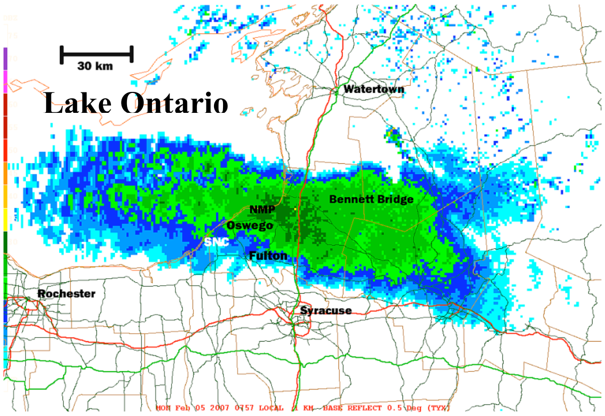

Figure 2. Base reflectivity image at 0757 UTC 5 February 2007 from Montague, NY radar (KTYX). NMP is Nine Mile Point nuclear power station.

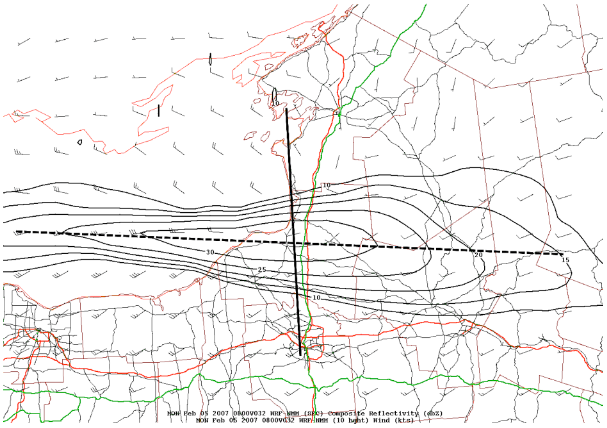

Figure 3. WRF-simulated composite reflectivity (dBZ) and 10-meter wind (kt) for the 32-h forecast verifying at 0800 UTC 05 February 2007 (about the same time as the radar image in Fig. 2). Solid line (length 111 km) denotes cross-section shown in Fig. 4 and the dashed line denotes cross-section in Fig. 5.

Comparing Figures 2 and 3 shows the model did a fairly good job representing the band location, width, and intensity at this time. The surface wind field shows a distinct convergence zone feeding the band (southwest winds to the south of the band over both water and land, and northwest winds to the north of the band, especially over the water). The wind speeds approached 30 kts near the band, with lesser speeds farther from it.

Figure 4 shows a south-north cross section through the band core’s short axis (see Fig. 3 for location). The aforementioned low-level convergence was part of a thermally-direct mesoscale transverse circulation with rising air in the warm core of the band and sinking motion on its edges. The potential temperature gradient was greater to the south as this air was above a cold land surface. Note the 10 dBZ contour of the band extended upward to near 650 mb and that the warm core and upward branch of the circulation is tilted to the south with height. The circulation was deeper over the lake on the north side of the band than on the south side. Also, the isentropes extend upward above the band core suggesting local adiabatic cooling due to the lifting of stable air.

The along-band cross section (see Fig. 5 and 3) reveals a well-mixed boundary layer (potential temperature constant with height to near 800 mb) over the lake, but an extremely stable layer of air (strong upward vertical potential temperature gradient) over the land immediately east of Lake Ontario. The warm core structure is still observed near 750 mb as the isentropes descend in the area of greatest vertical extent of the reflectivity contours. The band was strongest along the coast as the maximum reflectivity values and contour heights occurred there. This is a surprising find as the main topographical forcing by the Tug Hill Plateau is several tens of km inland, where lake-effect snowfall typically is the greatest [see snowfall climatology map at NWS (2008c)]. The air motion along the plane of this cross section was nearly parallel to the isentropes ascending as the parcels approached the coast. This enhanced the storm’s vertical reflectivity structure immediately along the shoreline. We believe a coastal front-like feature (Ballentine 1980) has developed along the eastern Lake Ontario shoreline, with cold air being wedged along the western side of the Tug Hill Plateau. This enhanced the snowfall rate well west of the plateau as seen in the observed and simulated reflectivity fields of Figs 2 and 5, respectfully.

Figure 6 shows similar model fields as those in Figs. 4 and 5, but through the short axes of wind-parallel roll-type snow bands. Four bands are shown in this southwest-to-northeast cross section as they extend inland from the northwest-to-southeast across the southeastern shoreline of

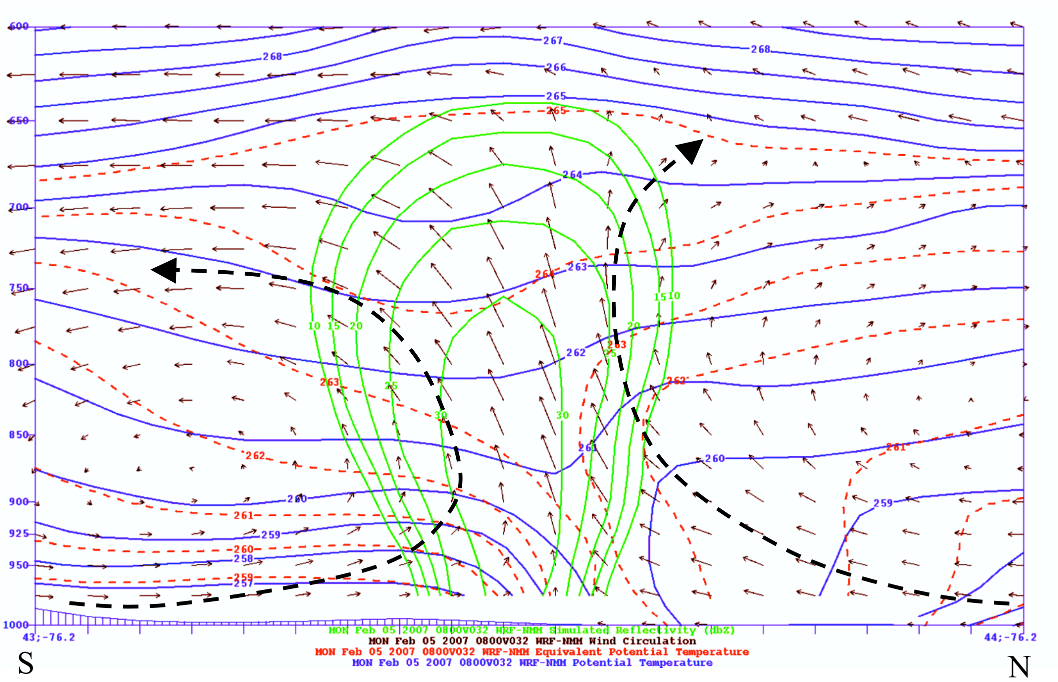

Fig. 4. South-to-north cross section (43°N to 44°N as shown in Fig. 3) from an 8-km, 31-level NMM simulation of the "Locust" storm at the same time as in Figs. 2 and 3 (0800 UTC 5 February 2007). Potential temperature (K, solid blue), equivalent potential temperature θ_e (K, dashed red), simulated reflectivity (dBZ, solid green), and arrows denoting wind scaled to cross section.

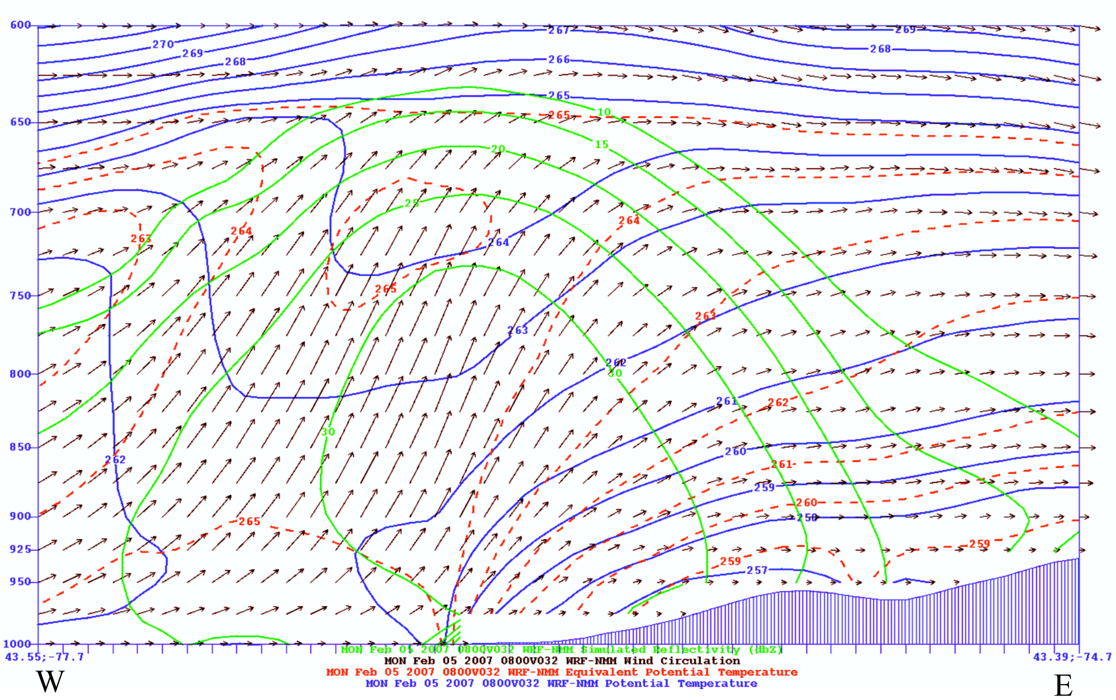

Fig. 5. A nearly west-to-east cross section along the major axis of the snow band shown as a heavy dashed line in Fig. 3. Contours and time same as in Fig 4.

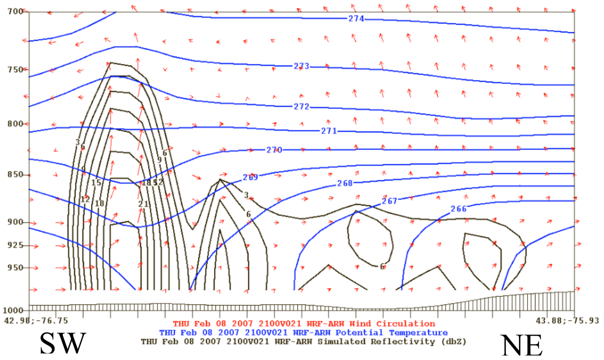

Figure 6. Southwest-to-northeast cross section of WRF-ARW simulated wind-parallel roll-type lake-effect snow bands at 21 UTC 8 February 2007. Simulated reflectivity (dBZ, black), isentropes (K, blue), and circulation vectors are shown.

Lake Ontario. A primary band is shown as an upward extension of reflectivity values in the far southwestern portion of the section. The isentropes extend downward near the band core, showing a slight warm core structure. Low-level convergence and upward motion are also depicted with this band.

The three other bands are much weaker (shallower, with maximum reflectivity ~ 6 dBZ versus the > 30 dBZ values associated with the LLAP band in Fig. 4). There were no thermal perturbations or distinct circulations associated with these bands as each successive band to the northeast was embedded in colder air.

4. COOPERATIVE INTENSIFICATION MECHANISMS IN LLAP BANDS

A cooperative intensification process known as Conditional Instability of the Second Kind (CISK) was proposed by Charney and Eliassen (1964) to describe the self-amplification and rapid development of some tropical systems. It is a cooperative process between the cumulus-scale convection and mesoscale flow field of tropical storms where the latent heat released by condensation develops a warm core structure. This warm core develops a thickness increase between two pressure surfaces in the middle of the storm and leads to low-level convergence there. This low-level moisture convergence then initiates more convection and the positive feedback loop is complete. The key environmental conditions for CISK to be released are that the environment be conditionally unstable and there by ample moisture to feed the storm.

We are proposing a similar dynamical approach for long lake axis-parallel (LLAP) intense lake-effect storms. Similar to tropical storms, these storms form within a conditionally unstable atmosphere, albeit much shallower than in the tropics, with an essentially unlimited moisture resource, the lake. Figures 4 and 5 show these lake storms are warm-cored heat engines with low-level convergence and upper-level divergence (see Fig. 7 for an example of diffluent flow aloft shown by the radar reflectivity field of one of these storms). Our data are model-derived, but Byrd et al. (1991) launched a radiosonde into one of these LLAP-type bands and measured a temperature that was 2.5°C warmer inside the band versus outside, but little of this difference was found for weaker multiple bands. Byrd et al. attribute most of this warming to "sensible heating of the boundary layer air by the lake-induced surface convergence" as latent heating was likely minimal due to the low temperatures. The relative contributions from latent and sensible heating to the warm core structure of LLAP bands will have to be tested with more observations and modeling of several storms.

We propose to call this theory "Linear CISK" as it operates along a band of convection as compared with the CISK Charney and Eliassen (1964) discussed with reference to circular systems. The thickness gradient and convergence field occur all along the band.

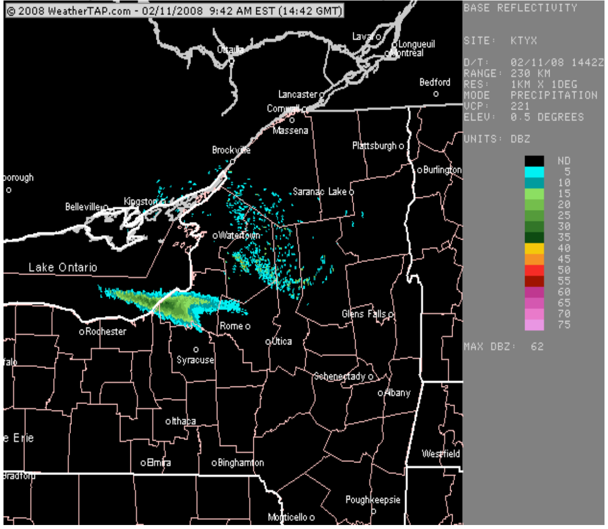

Figure 7. Radar reflectivity image of a lake-effect snow band over southern Oswego County at 1442 UTC 11 February 2008. Note the "V-notch" (similar to what is observed with supercell thunderstorms) at the southeastern end of the band representing strong diffluence.

LLAP-type lake-effect storms have been noted to intensify rapidly and persist longer than synoptic conditions would suggest [based on the authors personal experience while living in Oswego, NY and discussions with National Weather Service (NWS) forecasters]. The authors have noticed these bands last several hours into a warm air advection regime under a lowering capping inversion. Indeed, NWS personnel from the Buffalo, NY office have expressed frustration with intense snowfall rates (> 2 cm hr^{-1}) occurring in these bands several hours after a lake-effect snow warning has expired.

The Wind-Induced Surface Heat Exchange (WISHE) hypothesis proposed by Emanuel (1986) can also be related to LLAP lake-effect storm development and may be more appropriate as this theory includes surface heat fluxes. We have observed and modeled stronger surface wind speeds near the edges of these bands. The increased wind speed can enhance sensible heating and evaporation rates off of the lake and increase the latent heat flux into the storm. This process, in turn, can then lead to a stronger thickness gradient and wind response and complete the positive feedback process. Indeed, LLAP bands are more susceptible to greater fluxes as waves and surface roughness increase with greater fetch.

5. LAKE-TO-LAKE BAND CONNECTIONS OVER LAKE ONTARIO

The geography of the five Great Lakes (proximity of each lake to each other) supports the development of lake-effect storm interaction between bands. These interactions include both direct (two bands connected in a reflectivity field) and indirect effects (the moisture, thermal, and circulation fields of one band influence a downwind storm). These connections are important as they can influence downwind band location and intensity (Rodriguez et al. 2007).

Lake Ontario is the farthest downwind Great Lake in the climatological westerly flow that crosses the Great Lakes region during the cool season. Hence, it can take advantage of heat and moisture fluxes from one to two upwind lakes, mainly Superior and Huron. For an average winter, this was shown to occur 34% of the time, about 6 events per winter season (Rodriguez et al. 2007 used visible satellite data and hence these statistics are considered underestimates). Figure 8 shows an example of a lake-to-lake snow band connection between Lakes Huron and Ontario (notice two bands, one off of Georgian Bay and the other off the main part of Huron, converging into one intense LLAP-type band over Lake Ontario). This situation is a common occurrence during lake-effect events under west-northwesterly flow. The WRF modeling system captures this interaction quite well, but significant (~10 km) forecast band location error was found for other cases of lake-to-lake interaction (Ballentine and Zaff 2007). We believe these lake-to-lake connections play a pivotal role in developing the most significant lake-effect snowstorms that can paralyze a community downwind of the lower Great Lakes (e.g., Lake Storm “Locust” dumped 350 cm in Redfield, NY in February 2007; NWS Buffalo 2008b). Further research is needed to determine the environments conducive to their formation (Rodriguez et al.)

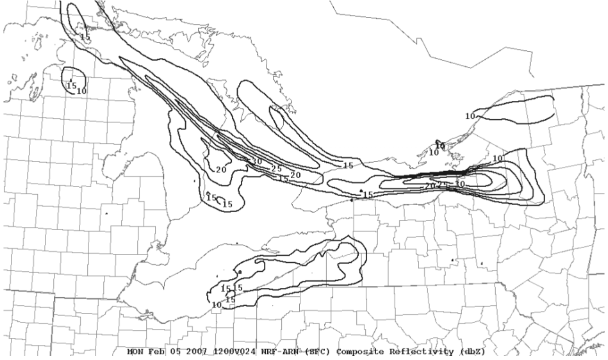

Fig. 8. WRF simulated composite reflectivity (dBZ) for 12 UTC 5 February 2007 (a 24 hour forecast). Note the lake bands connecting between Lake Huron and Ontario.

6. LAKE-EFFECT LIGHTNING

Moore and Orville (1990) showed lake-effect storms with cloud-to-ground (CG) lightning were of the long lake axis-parallel type (LLAP) discussed in this preprint, with most of the lightning occurring downwind of the longest axes of Lakes Erie and Ontario for specific events. Figure 9 (from Steiger et al. 2008) shows the climatological CG flash density associated with lake-effect storms (all precipitation types) during the period 1995-2007. Flash density values greater than 0.26 flashes km^{-2} (> 7 flashes in a 25 km^2 grid box) were observed at the eastern ends of the lower Great Lakes, and the lightning had little inland extent.

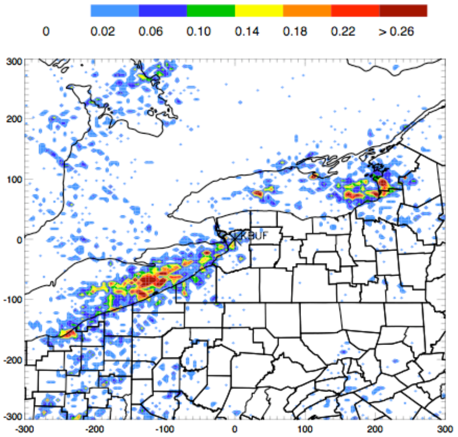

Fig. 9. Cloud-to-ground lightning flash density (flashes km^{-2}) in the lower Great Lakes for lake-effect storms during the 1995-2007 period. Distances (km) south-north and west-east of Buffalo (KBUF) are also shown. From Steiger et al. (2008).

Approximately six lake-effect thunderstorm events occur each season over the eastern Great Lakes (Erie and Ontario; Steiger et al. 2008). Steiger et al. only studied the region around these lakes as the lake-effect band types most responsible for lightning (LLAP or shore-parallel bands) occur more frequently there (Kristovich and Steve 1995). Future research will be to extend this analysis to the Upper Great Lakes. They found one storm event produced well over 1500 CG flashes! Most events occur from November through December, when the lake surfaces are warmer and have greater heat and moisture fluxes. The precipitation type associated with lake-effect thunderstorms vary from rain to snow as the cool season progresses, but the majority of events are snowstorms.

We believe most of the lightning which occurs during lake-effect thunderstorms is being missed by the National Lightning Detection Network (NLDN; Cummins et al. 2006). One lake-effect event on 2 December 2005 had well over 20 instances of lightning/thunder, but the NLDN only detected 5 CG flashes. Total lightning networks (e.g., Lightning Mapping Array, Krehbiel et al. 2000) need to be utilized to better document and understand these storms. In addition to in-situ observations, these data can provide information on the thresholds for lightning initiation in clouds.

Two environmental characteristics were found useful by Steiger et al. (2008) in forecasting lightning in lake-effect storms: the lake-induced equilibrium level (EL) and altitude of the -10°C isotherm. Deeper, warmer clouds can develop more graupel and separate electrical charge to the point of lightning initiation. Lake-effect storms, especially the LLAP-type, can be quite convective surface-based storms.

7. CONCLUSIONS

We have presented both observational and model data of the structure and characteristics of the most frequent weather hazard (and disaster) to residents of the eastern Great Lakes region, the long lake axis-parallel (LLAP) lake-effect snowstorm. They differ in several aspects compared to wind-parallel roll-type (WPR) lake-effect storms more common to the western Great Lakes region in the following ways:

1) LLAP storms can have excessive snowfall rates (> 8 cm hr^{-1}) and storm totals (>130 cm) associated with them more frequently than experienced with WPR storms,
2) Model data suggests these are significant warm-core storms with a distinct transverse circulation with a strong mesoscale low-level convergence field and outflow aloft, and
3) LLAP-type storms can be electrified, sometimes producing lightning rates approaching that of a typical warm season thunderstorm.

A cooperative feedback process known as Conditional Instability of the Second Kind (CISK; Charney and Eliassen 1964) is proposed to explain the behavior of LLAP lake-effect storms. There are similarities in the structure and dynamics of lake-effect and tropical storms (e.g., warm core structure developed by latent heat release, feed off of warm water and abundant supply of moisture, develop quickly and sometimes persist when synoptic conditions become unfavorable). Hence we have applied the theories of CISK and WISHE (Emanuel 1986) to a linear storm (hence, "linear CISK"). Much more research is needed to support and develop these ideas, especially observational data as most of what we know about the structure of these bands is from numerical data.

Lake-effect lightning occasionally occurs across the eastern Great Lakes and is associated with the LLAP-type bands. These storms serve as an ideal laboratory to answer basic science questions regarding the relationships between microphysics and the charge separation necessary for lightning initiation as they form in cold environments and do not typically produce high flash rates. We also have no information on the *total* lightning (intracloud and cloud-to-ground) production by lake-effect storms.

A lot of what we have learned about long lake axis-parallel lake-effect storms has been from model output. We need more direct, in-situ observations to confirm these findings and test the proposed hypotheses to explain them. SUNY Oswego has recently received an NSF Major Research Instrumentation (MRI) grant for surface and mobile upper-air facilities, including a radiosonde and tethersonde system, that will be invaluable to further this research.

The 5 February 2007 case discussed in sections 3 and 4 occurred in a very cold environment (surface temperatures at 00 UTC 5 Feb. were near -15°C). It will be useful to study lake-effect case studies with a variety of environmental conditions to observe how prevalent the structures discussed in this preprint are (e.g., cold air damming occurring on the western Tug Hill Plateau).

8. ACKNOWLEDGEMENTS

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